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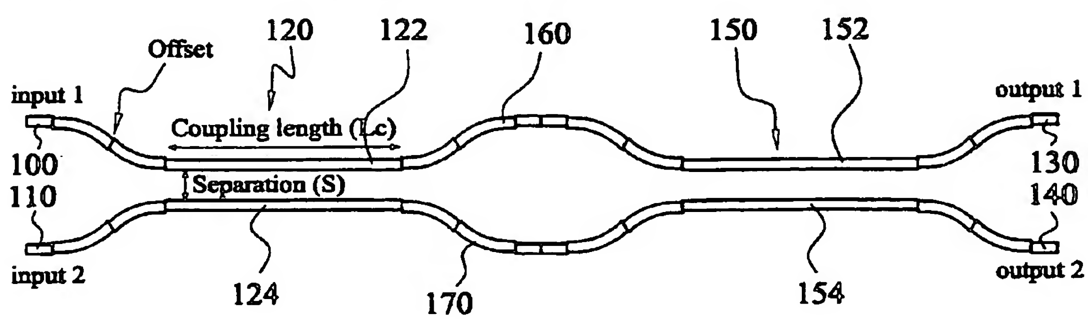

Layout of an MZI

(57) Abstract: An optical device comprises a substrate on which is provided two input waveguides (100, 110) connected to a first optical coupler (120), two output waveguides (130, 140) connected to a second optical coupler (150), and a pair of waveguide arms (160, 170) connected between the two couplers, wherein the first optical coupler comprises two waveguide portions (122, 124), a first one of which has a greater relative width than the second, and wherein the second optical coupler comprises two waveguide portions (152, 154), the first one of which has a smaller relative width than the second, the first waveguide portion of the first coupler being connected by a first one of the waveguide arms to the first waveguide portion of the second coupler, and the second waveguide portion of the first coupler being connected by the second waveguide arm to the second waveguide portion of the second coupler.

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OPTICAL DEVICE

This invention relates to optical devices, and in particular to directional couplers used in Mach-Zehnder Interferometer (MZI) devices.

Integrated optical devices have many uses in the fields of optical communication, optical sensing and optical processing. These are optical components formed by depositing or fabricating waveguide structures on a planar substrate.

This technique has many established advantages over the use of discrete optical components based on fibre or bulk optical technology. Many separate functional components can be fabricated on a single substrate, saving manufacturing costs and allowing the temperature and other environmental conditions to be equalised across the group of components. The waveguides on an optical integrated circuit can often follow curves which are far too tight for optical fibres. Also, the waveguide material can be chemically altered in various ways, or even substituted by a different material such as a polymer, without having to allow for the mechanical stress of the fibre drawing process or the need to maintain the physical strength or integrity of the waveguide.

Figure 1 of the accompanying drawings schematically shows a typical structure of an optical integrated circuit. In the example shown, a silicon substrate 10 has a thermally grown silica (SiO_2) buffer layer 15. A waveguide core 20 is fabricated by depositing a layer of silica, doped for higher refractive index, for example by flame hydrolysis deposition followed by a consolidation step, and then etching away all but the required waveguide core. A cladding material 25 such as silica but doped so as to be of lower refractive index than the waveguide core is then deposited over the waveguide core structure. A heating element 35 over the core is also illustrated.

Figures 2a to 2b of the accompanying drawings schematically illustrate typical optical components formed using the above techniques. The components comprise input waveguides 40, a first optical coupler 45 functioning as a splitter, a pair of waveguide arms 50 and a second optical coupler 55, functioning as a combiner with these parts in combination forming a Mach-Zehnder interferometer (MZI) arrangement.

These devices are particularly useful because the optical path length along one or both of the arms can be varied. For example, if a heating element 35 such as a thin track of an electrically resistive metal is fabricated on the cladding layer over one of the arms, that arm can be heated and the change in temperature caused in turn alters the optical path length of that arm. In this way, integrated optical MZIs can form functional parts of switches, routers, attenuators and the like.

Light supplied along an input waveguide, say input 1, is split between the two waveguide arms. After propagation along the arms it is recombined at the combiner (which in the devices shown has the same configuration as a splitter). The output from there depends on the relative phase of the two signals at the combiner, which in turn depends on the relative optical path lengths of the two arms. If the two signals are in phase at the combiner, for example when both arms are of equal length, then substantially no bar-state output signal will be generated, that is at output 1, and the signal will be switched to output 2. A different phase difference will lead to a greater output signal on output 1, with a maximum being obtained at a 180° phase difference. When the differences between the phase of the signals at the combiner is $\pm \pi/2$ the signal is split equally between the two outputs.

As shown in Figure 2b an extra phase-shift of π can be introduced by making one of the waveguide's arms longer. This makes it possible in the unpowered (off-) state to switch input one to output one.

One disadvantage of having waveguide arms of different lengths, is the extra curves required in the longer arm, which probably will cause some extra bend loss and scattering losses. However, bend losses can be reduced by using offsets between the curves of a waveguide.

When a directional coupler is used as a 3dB-splitter, which splits an input signal 50:50 between two outputs, various different configurational options can be chosen. The first option is to use symmetrical waveguides (both waveguides having the same width and shape) with a coupling length (L) of $\frac{1}{2}L_c$ where Lc is the coupling length for full coupling of a signal from one waveguide to the other. Another option is to use asymmetrical waveguides (both waveguides have different shape and/or widths), with coupling lengths of Lc.

The advantage of the second option is that the structure is not so dependable on wavelength variation, because the variation in the coupling length is more tolerable.

To obtain strong coupling, the coupling length must be as small as possible. This can be seen in the following equation:

$$L = \frac{\pi}{(\beta_0 - \beta_1)} = \frac{\pi}{2\kappa}$$

With β_0=propagation constant of the even super-mode and β_1=propagation constant of the odd super-mode, and κ=coupling coefficient.

Figure 3 of the accompanying drawings shows the configuration of a directional coupler. This comprises two waveguides with curved input/output sections 70, 72 and a coupling region there between of length L. In the coupling region the two waveguides are separated by a distance 'S'.

Figures 4 to 7 show various possible different types of coupler which can be achieved by changing the waveguide cores in the coupling region. Figure 4 shows a symmetric directional coupler in which the two arms of the coupler have the same cross-sectional geometry and refractive index profile; Figure 5 shows an asymmetric coupler with straight waveguides, but of different widths, D1 and D2; Figure 6 shows an asymmetric coupler with one tapered and one straight waveguide; and Figure 7 shows an asymmetric coupler with two tapered waveguides.

Symmetric couplers have very good coupling ratios, ranging from 0 to 1. However, they have a very wavelength dependent response (i.e. power output varies with wavelength of input light). In many applications, directional couplers with a substantially wavelength independent response or wavelength flattening properties(i.e. compensation for wavelength dependence), are desirable. For a symmetric directional coupler, the coupling coefficient only approximates to being wavelength independent in the wavelength range of from 1500 to 1600nm, for a difference between the refractive index of the waveguide core to that of its surrounding cladding, of 0.25%. With this refractive index difference the required waveguide dimensions and

separation fall within possible fabrication tolerances. For example 5.8μm for the waveguide width and 6.5μm for the separation, 'S'.

However, when the refractive index difference is greater than this, for example 0.5%, the required separation, for example, becomes about 0.01μm and the waveguide widths about 5μm. Such dimensions often do not meet bulk processing tolerances, and instead require dedicated and expensive fabrication processes to be used. Also at this kind of separation the coupling coefficient is very high, resulting in a very short coupling length (≈350μm).

Furthermore, in symmetric couplers the bends in the waveguides (prior to the coupling region) introduce an extra phase shift, so the light signals have already coupled once before they reach the intended coupling region. When the light has coupled once the next total coupling will be less than 100% (i.e. giving a non-zero coupling ratio), so we believe the configuration of a symmetric directional coupler is not in practice suitable for making a wavelength flattening 3-dB splitter. (See also the below discussion regarding extinction ratios and non-zero coupling ratios.)

Asymmetric couplers of the type shown in Figure 7 are wavelength flattening because the phase difference between the odd and even mode accumulated over the first half of the coupler length is reversed over the second half. One disadvantage of these couplers is that the coupling ratio of these types of couplers is not as good as that of a symmetric coupler.

Asymmetric couplers of the type shown in Figure 6 with one straight and one tapered waveguides have the worst properties. Table 1 shows an overview of the minimum and maximum coupling ratios of different kinds of couplers.

Table 1

Type of Coupler	Symmetry		Coupling ratio		Wavelength-flattening
	Line-Sym.	Point Sym.	Min	Max	Response
Symmetric	Yes	Yes	0	1	Bad (No $\Delta\beta$)
Asymmetric I (straight waveguides)	Yes	No	0	<1	Excellent (constant $\Delta\beta$)
Asymmetric II (tapered waveguides)	No	Yes	>0	1	Good (reversed $\Delta\beta$)
Asymmetric III (straight and tapered waveguide)	No	No	>0	>1	Bad (slight $\Delta\beta$)

The most important parameter of Table 1 is the minimum coupling ratio, because this determines the maximum extinction ratio. It is desirable for the maximum extinction ratio to be as large as possible. The extinction ratio is often quoted as the difference between the power $P_1^{=}$ of the signal output from one output channel of the coupler device in its 'on' state (i.e. "bar" state) and the power P_1^{x} of the signal output from the same output channel of the device in its 'off' state (i.e. "cross" state). A non-zero coupling ratio means a lower extinction ratio. It can be seen from Table 1 that the configuration with two tapered waveguides is not suitable for obtaining high extinction ratio, although it does show a good wavelength response.

The optical device of the present invention has been found to have improved characteristics.

The present invention provides an optical device, such as a Mach-Zehnder Interferometer (MZI), comprising a substrate having two input waveguides connected to a first optical coupler, two output waveguides connected to a second optical coupler, and a pair of waveguide arms connected between the two couplers, wherein the first optical coupler comprises two waveguide portions, a first one of which has a greater relative width than the second, and wherein the second optical coupler comprises two waveguide portions, the first one of which has a smaller relative width than the second, the broader waveguide portion of the first coupler being connected by a first one of the waveguide arms to the narrower waveguide portion of the second coupler, and the narrower waveguide portion of the first coupler being connected by the second waveguide arm to the broader waveguide portion of the second coupler.

The invention will be defined in more detail in the appended claims to which reference should now be made.

Preferred embodiments of the invention will now be described with reference to the drawings in which:

Figure 1 schematically illustrates a typical structure of an optical integrated circuit;

Figures 2a and 2b schematically illustrate typical Mach-Zehnder Interferometers (MZIs);

Figure 3 shows the configuration of a directional coupler with offsets at the bends;

Figure 4 shows the configuration of a symmetrical coupler;

Figure 5 shows the configuration of an asymmetric coupler with straight waveguides

Figure 6 shows the configuration of an asymmetric coupler with one tapered and one straight waveguide;

Figure 7 shows the configuration of an asymmetric coupler with two tapered waveguides;

Figure 8 shows an optical device according to an embodiment;

Figure 9 represents schematically a possible configuration of a TOS in one embodiment of the invention;

Figure 10 shows a cross-section through the arms of an MZI;

Figure 11 shows the configuration of a combination of 2x2 TOS switches according to another embodiment;

Figure 12 shows the layout of the waveguides in the switch of Figure 11;

Figure 13 shows the possible layout of the waveguides in a single stage 2x2 TOS; and

Figure 14 shows the function of a low cross-talk switch.

Referring to Figure 8, the optical device of an embodiment provides a planar substrate (not shown) on which there are two input waveguides 100, 110, connected to a first optical coupler 120, two output waveguides 130, 140, connected to a second optical coupler 150 and a pair of waveguides arms 160, 170 connected between the two couplers 120, 150. Each of the first and second couplers comprise a pair of waveguide portions 122, 124, 152, 154, each one of a pair having a relative different width to the other of the pair. The waveguide portions are arranged such that the first-coupler waveguide portion of greater relative width is connected to the second-coupler waveguide portion of smaller relative width; and the first-coupler waveguide portion of the smaller relative width is connected to the wider of the two second-coupler waveguide portions. Thus the second coupler compensates for the phase-difference changes introduced by the first coupler, and has a compensating wavelength response to that of the first coupler, to produce a compensated wavelength-flattened response.

In a preferred embodiment the optical device functions as a switch, and the two couplers of the device each comprise two straight waveguides of different widths, the couplers being inverted with respect to one another.

For a device in which the difference, Δn, in the refractive index of the waveguide cores of the couplers to that of their surrounding cladding is 0.5% it is possible to make a 3-dB splitting directional coupler with dimensions which lie within fabrication tolerances, namely using waveguide portions of widths 6.0μm and 4.74μm respectively, with a separation of 3.7μm, and a coupling length of 800μm. The device is optimized to work at 1550μm.

The choice of Δn depends on the size of the device. The lower Δn is the lower the propagation losses are, but the larger also the bend radii will need to be to avoid high bend losses. If you have a higher Δn you can use a smaller radius of curvature for the bends as the light is better confined.

The system works through using a combination of the properties of Table 1. The devices of the preferred embodiments have the excellent wavelength flattening response for splitting of a straight asymmetric directional coupler, combined with the reversed accumulated phase-difference properties of a tapered directional coupler (Figure 7).

According to two embodiments of the invention, the MZI's of figures 2a and 2b can each employ the directional coupler described above as the coupler (55) and/or splitter (45).

Referring to Figure 9, a low power Thermo-Optic Switch (TOS) can be made by introducing an extra $\pi/2$ phase shift (at a wavelength in the middle of the desired range).

In the single Thermo-Optic Switch (TOS) of the embodiment of Figure 9, the bar state of the switch is defined as when a signal input on input 1 is output on output 1, with a signal input on input 2 being output on output 2. Conversely, the cross state, or x-state, is defined as a signal input on input 1 being output on output 2, with signals input on input 2 being output on output 1.

It has been found that the bar-state and x-state of this TOS have a WDL (Wavelength Dependent Loss) of 0.2dB, and a very good extinction ratio of less than

-30dB. This has been found to be a great improvement over switches using other configurations and combinations of couplers, such as combinations of Y-junctions and tapered waveguides or even over two asymmetric waveguides which are not arranged in the compensation configuration, with one inverted with respect to the other.

The compensation configuration has two main advantages, which lead to its good x-state extinction ratio. Firstly the configuration compensates in the second splitter for any deviation from a 50% split by the first splitter. Secondly the phase-wavelength dependency of the heater can be compensated. An introduced –90° physical phase-shift (from an extra path length in one waveguide arm), is compensated by a +90° phase shift introduced by the heater on that arm. Both phase shifts have the same but opposite phase-wavelength dependency. For this reason it is also possible to use this configuration as a Variable Optical Attenuator (VOA) by working in the x-state and using the output of the bar-state. At -20dB the VOA has a WDL of 1.08dB for a 1500-1600nm wavelength range.

Figure 10 shows a schematic cross-section through the arms of an MZI showing the typical parameters of the waveguide cores. In practice the parameters used often depend upon the size of the die used in fabrication.

Figures 13 show typical dimensions of a single stage MZI with asymmetrical, inverted directional couplers with input/output bends, showing the taper sections used to connect straight waveguide portions of greater width to curved portions of smaller width. These taper sections are required so that the width of the waveguides changes slowly enough that there is insignificant coupling of a transmitted signal with higher order modes. This is known as tapering adiabatically.

A plurality of the above described TOS's can be used to make a 2x2 TOS switch as shown schematically in Figure 11. To connect all the single stages a crossing is needed. This is preferably at 90°, for optimal functionality and minimal cross talk, but this requires a larger overall structure of the switch. To minimize the size of the switch the crossing angle α can be reduced to as little as 20°, although α>30° is preferred. In one embodiment the crossing angle is about 20°, the offset at the bends is about 650μm, and the bend length is about 6500μm with a cross-talk less than –45dB, a bend radius of 16.4μm and an insertion loss of 0.14dB. Another

example has a bend radius of 20μm, and an insertion loss of 0.07dB. The preferred widths and separation of the two couplers making up a TOS switch are as follows:

Width 1	=	6μm ± 0.2μm;
Width 2	=	4.74μm ± 0.2μm;
Separation	=	3.7μm ± 0.2μm; and
Coupling Length	=	800μm

Referring to Figure 12, this 2x2 TOS switch has eight heaters in total, and uses three heaters to switch each time. In the no power state the switch works in the broadcast mode. To make a blocking switch the power consumption increases by about double. The function of this 2x2 switch is explained in Table 2 below.

Table 2

From Input No.	To Output No.	TOS No.	State	Power On Heater No.
1	1	I II IV	X Bar Bar	1 4 8
1	2	I II IV	Bar X X	2 3 7
2	2	III II IV	X Bar Bar	5 4 8
2	1	III II IV	Bar X X	6 3 7

Referring to Figure 14, this configuration works as follows. When a light signal is launched in input 1 and is to be switched to output 1, the first single stage TOS gives an extinction ratio of 20 dB. Then the main power of the signal will go to the stage of output 1, and the small unwanted signal propagates to the second stage TOS for output 2. At the single stage TOS for output 2 the unwanted signal is further reduced by transferring this signal to the dummy output. This will give an extra 20 dB extinction ratio. So the total extinction ratio between the two outputs will become 40

dB. For switching the signal from input 1 to output 2 all the three single stages have to be switched.

The present invention provides an optical device which provides surprisingly good results combining a wavelength flattening response with a high extinction ratio. The device has many applications only some of which are mentioned here, but it finds particular use in TOS switches and VOAs.

CLAIMS

1. An optical device comprising a substrate on which is provided two input waveguides connected to a first optical coupler, two output waveguides connected to a second optical coupler, and a pair of waveguide arms connected between the two couplers, wherein the first optical coupler comprises two waveguide portions, a first one of which has a greater relative width than the second, and wherein the second optical coupler comprises two waveguide portions, the first one of which has a smaller relative width than the second, the first waveguide portion of the first coupler being connected by a first one of the waveguide arms to the first waveguide portion of the second coupler, and the second waveguide portion of the first coupler being connected by the second waveguide arm to the second waveguide portion of the second coupler.

2. An optical device according to claim 1, wherein the waveguide portions of the first and second couplers comprise waveguide cores of substantially constant width, with one waveguide core of each coupler having a greater width than the core of the other waveguide portion of the coupler.

3. An optical device according to claims 1 or 2, in which the first and second couplers are inverted with respect to one another.

4. An optical device according to claim 1,2 or 3 further comprising one or more heating and/or cooling arrangement(s) for altering the temperature of one or both of the waveguide arms.

5. An optical device according to any preceding claim in which one of the waveguide arms provides a greater optical path length than the other.

6. An optical device in which one or more waveguide portion(s) of coupler is connected to a waveguide arm and/or an input and/or an output waveguide via a tapered waveguide portion which is arrayed to adiabatically transmit optical signals.

7. An optical device further comprising offsets in the waveguide arms and/or the input and/or the output waveguides.

8. A thermo-optic switch comprises a device according to any preceding claim.

9. A 2x2 thermo-optic switch comprising four optical devices according to any of claims 1 to 7.

10. A variable optical attenuator comprising an optical device according to any of claims 1 to 7.

11. A Mach-Zehnder Interferometer comprising one or more optical device(s) according to any of claims 1 to 7.

12. An optical device substantially as described herein with reference to Figures 3 and 8 to 14.

13. A thermo-optic switch substantially as described herein with reference to Figures 3 and 8 to 14.

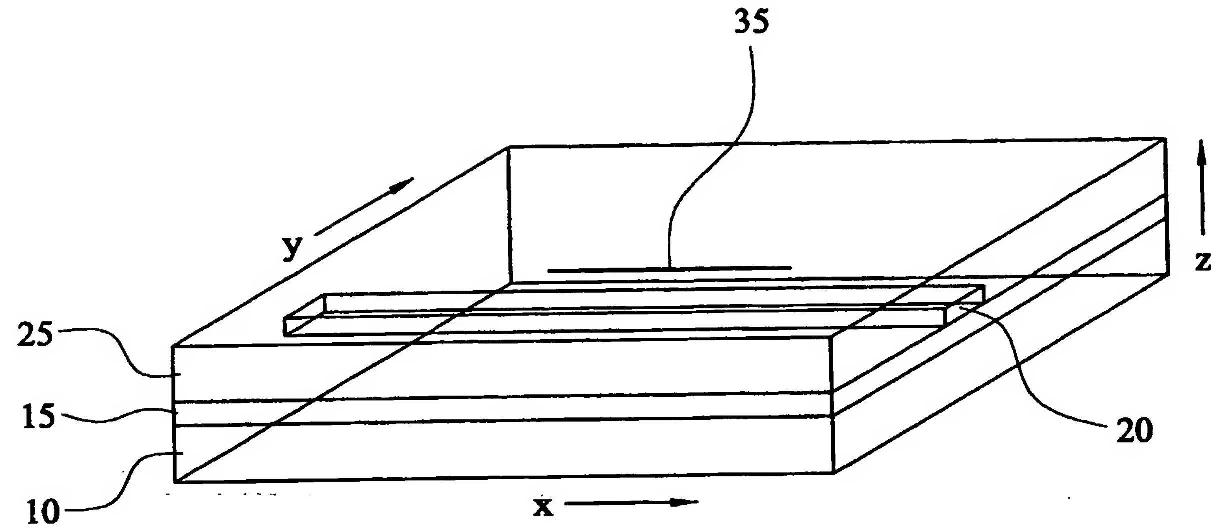


FIG. 1

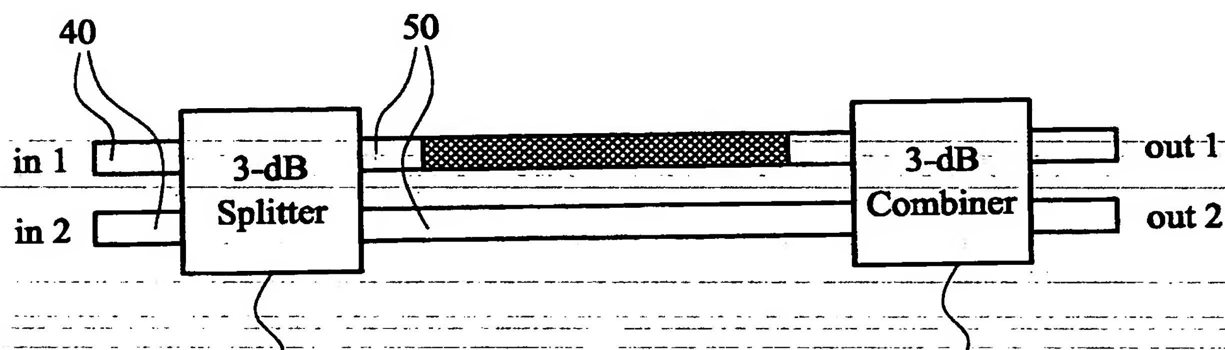


FIG. 2(a)

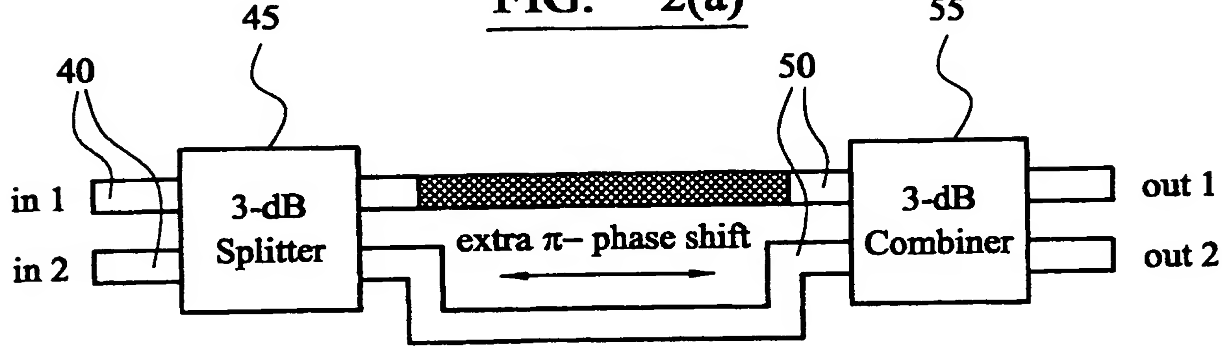
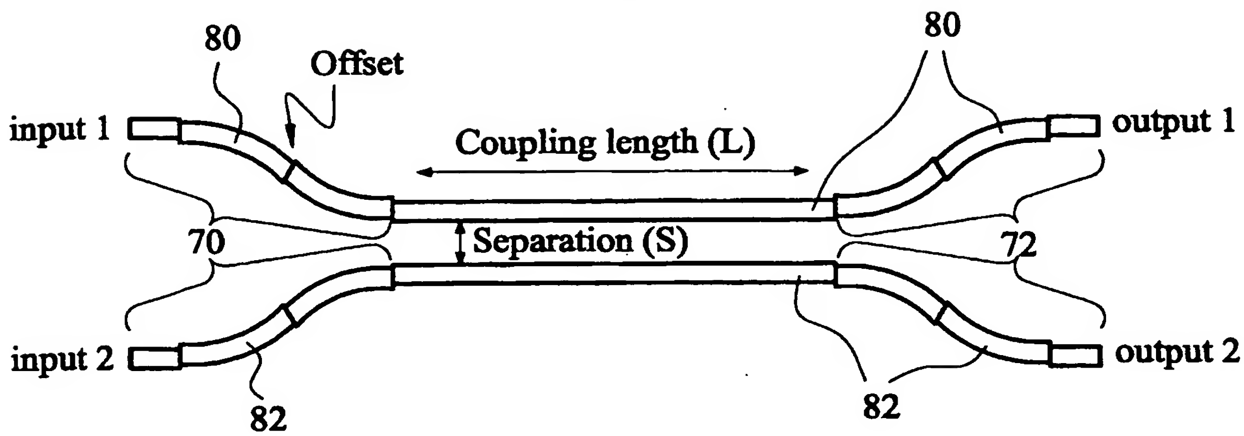
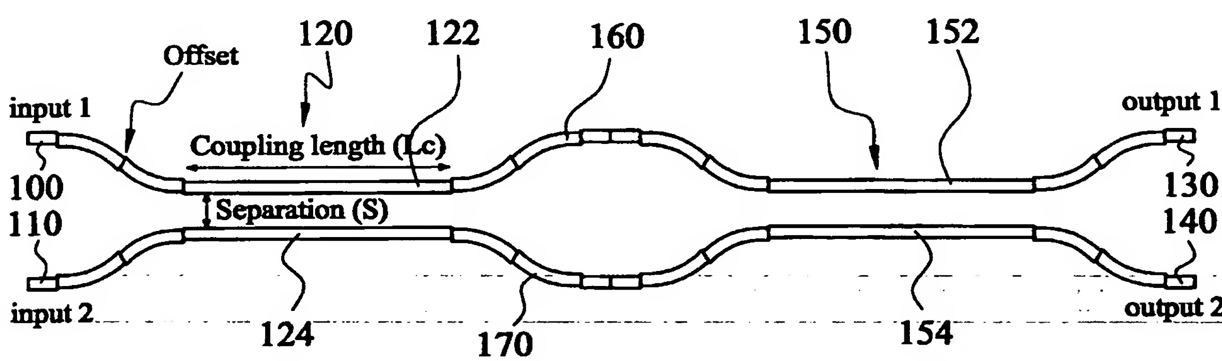


FIG. 2(b)



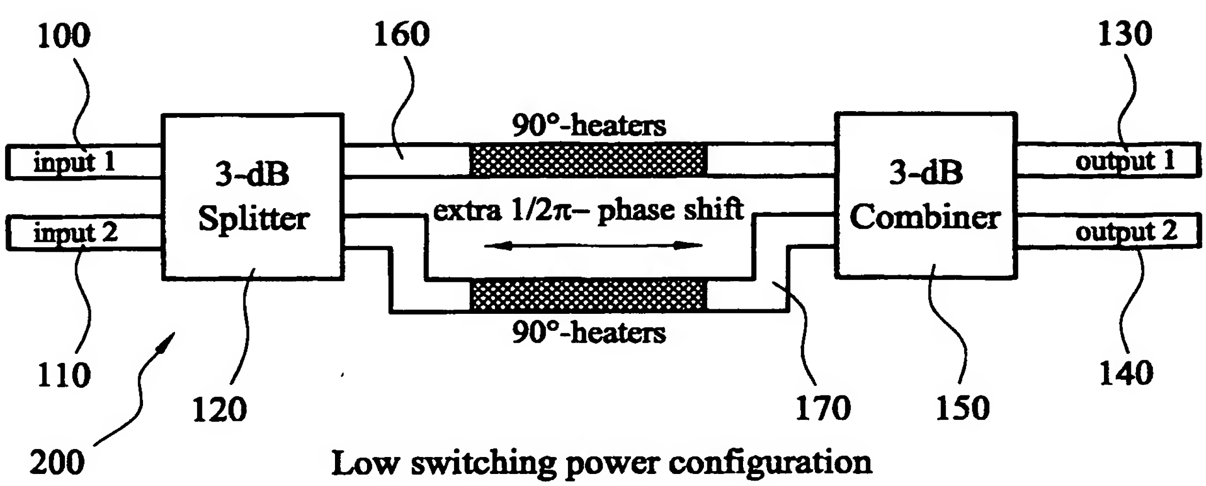
Configuration of a directional coupler

FIG. 3



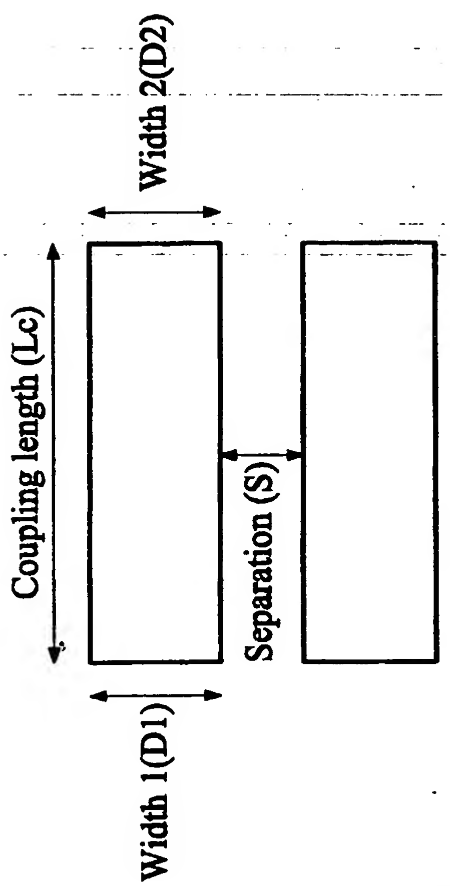
Layout of an MZI

FIG. 8



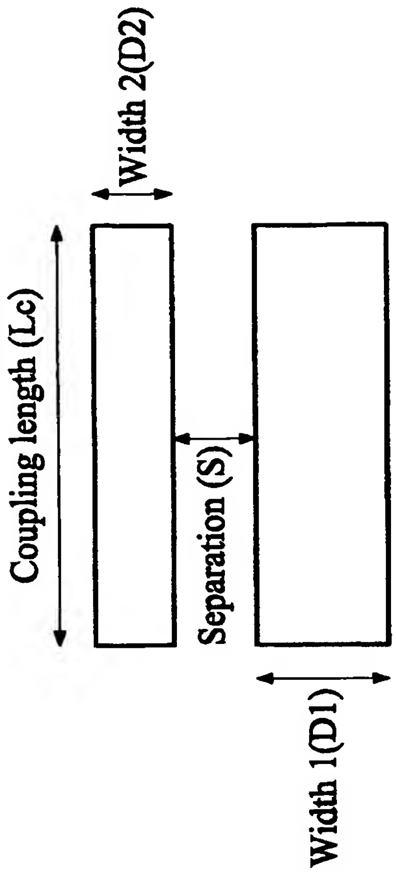
Low switching power configuration

FIG. 9



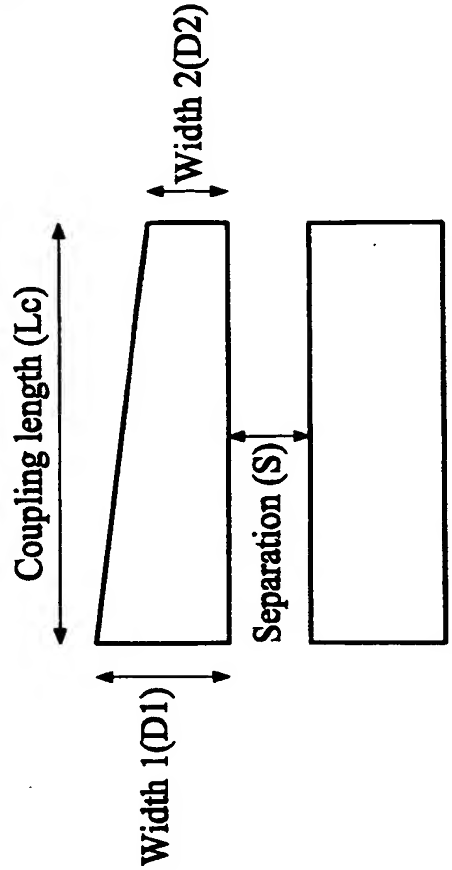
Symmetric directional coupler

FIG. 4



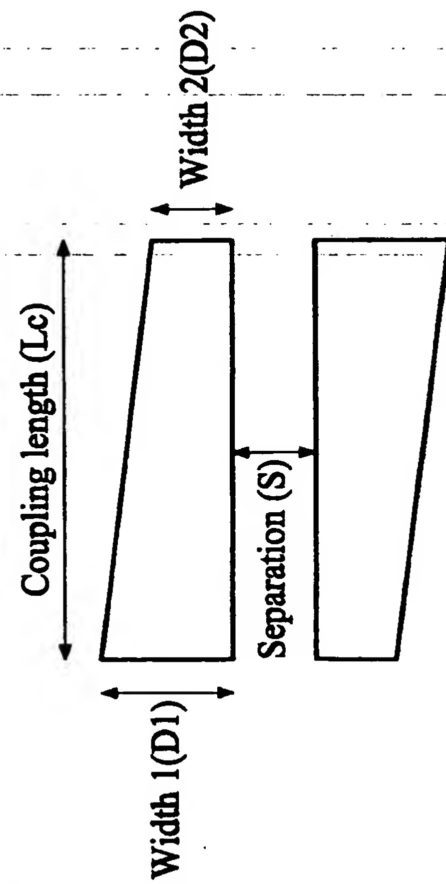
Asymmetric coupler with straight waveguides (I)

FIG. 5



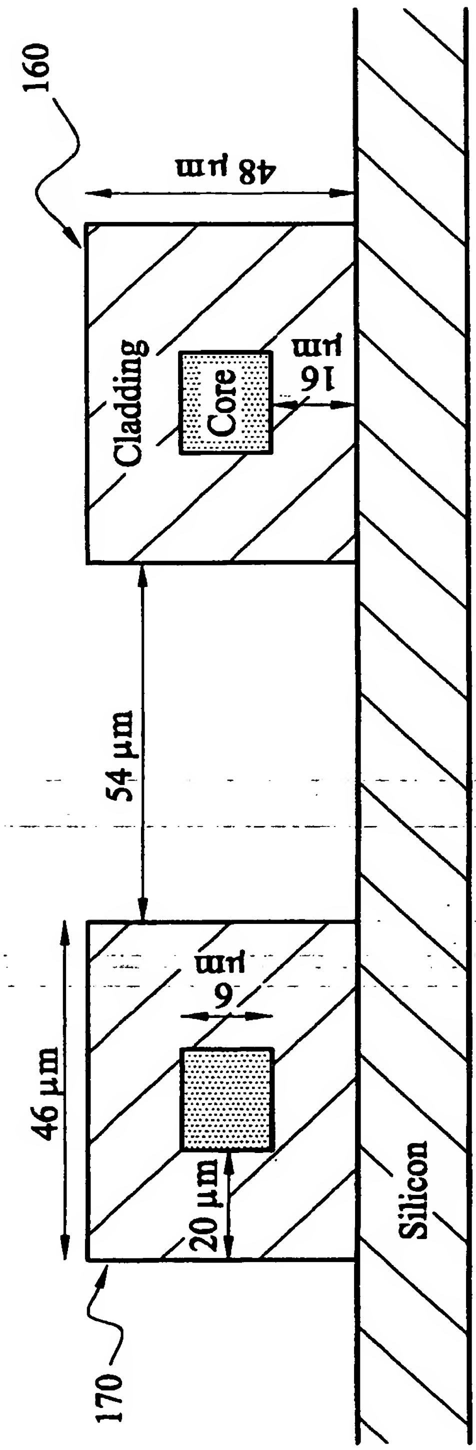
Asymmetric coupler with one tapered and one straight waveguide (III)

FIG. 6



Asymmetric coupler with two tapered waveguides (II)

FIG. 7



Cross-section of an MZI eg. along A - A in Fig. 12

FIG. 10

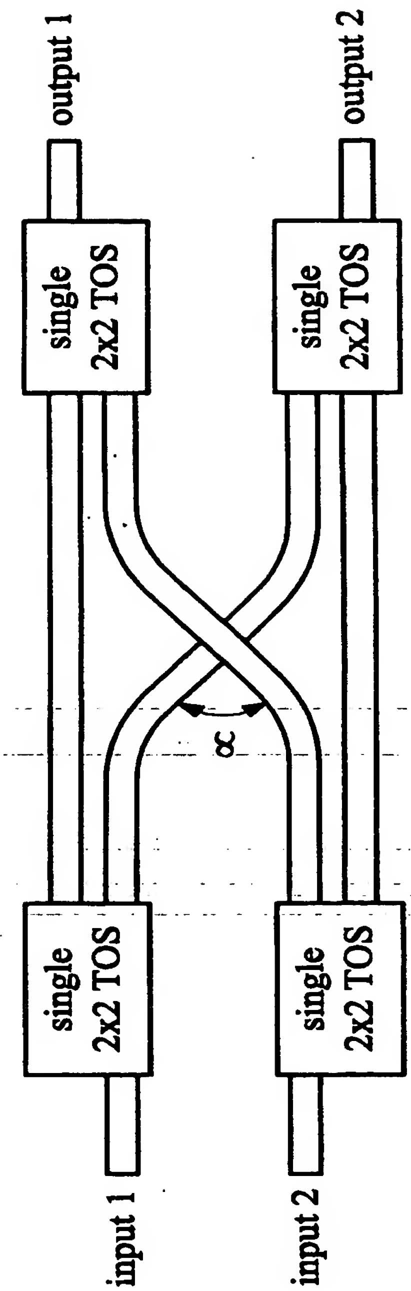
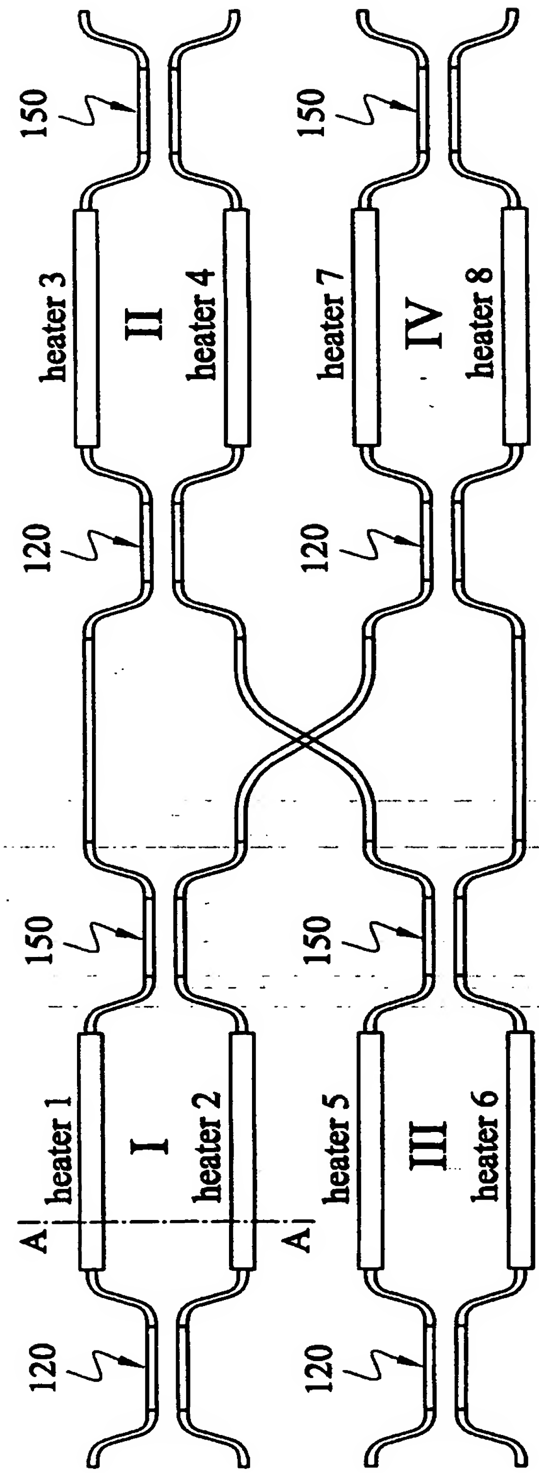
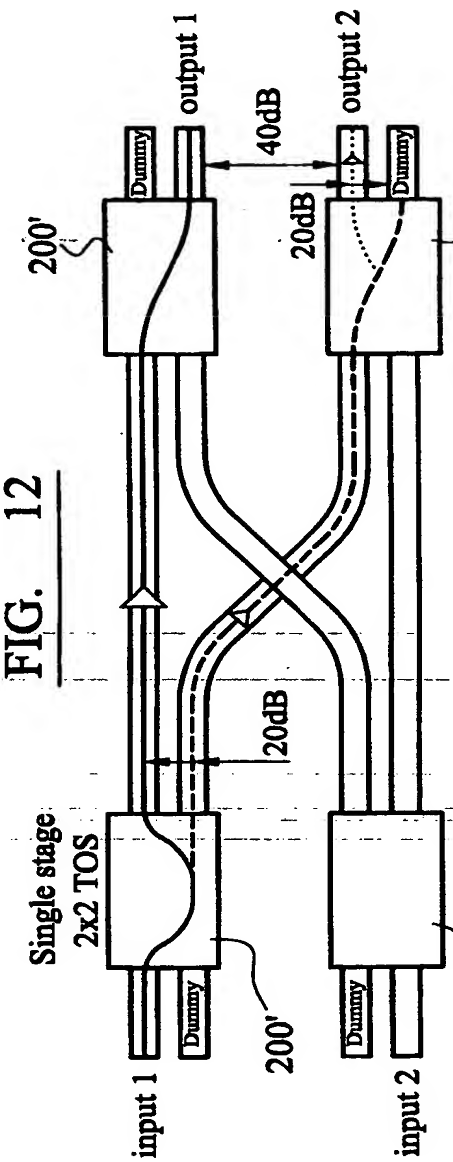


FIG. 11



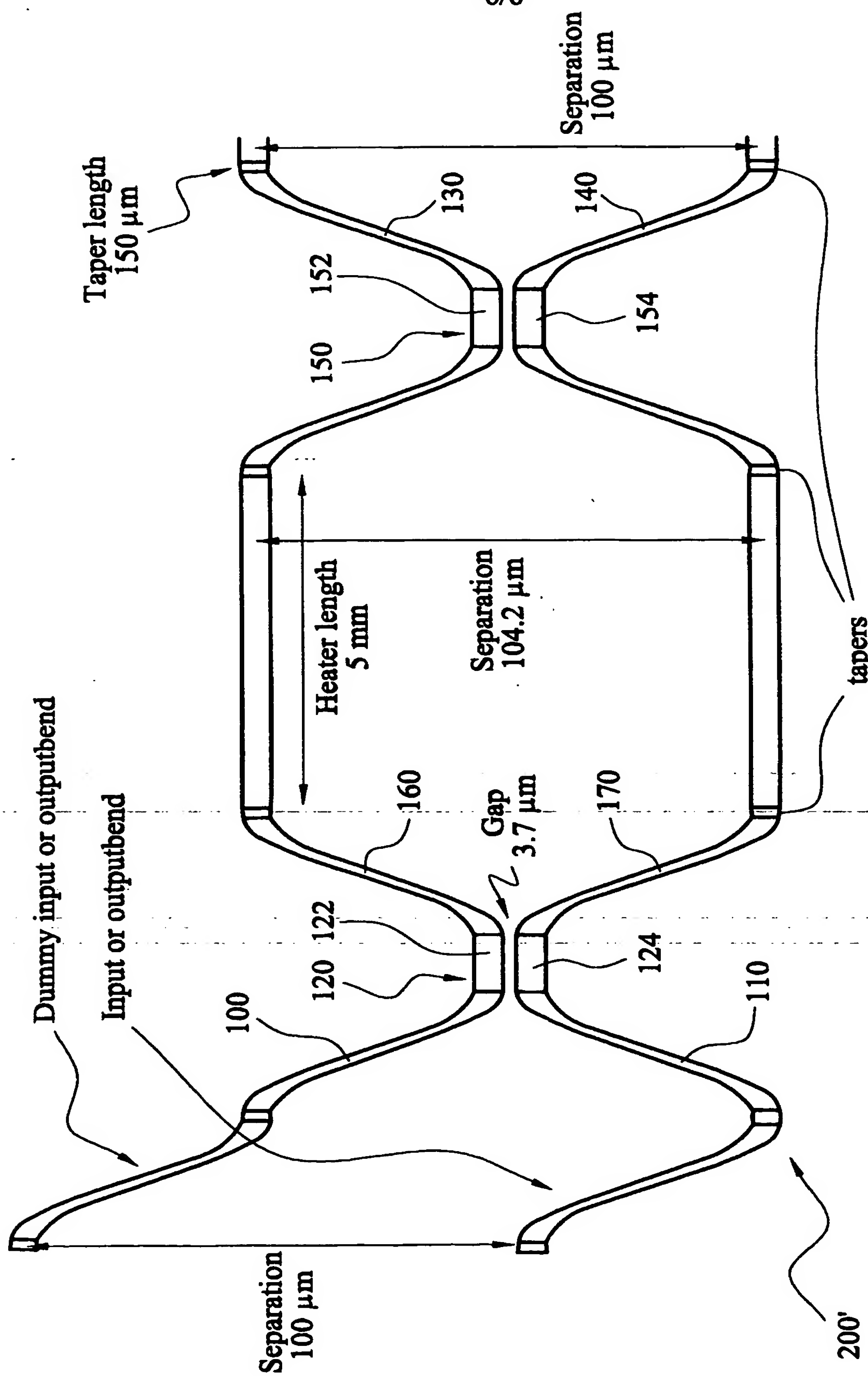
2 x 2 TOS SWITCH CONFIGURATION

FIG. 12



Configuration of the low cross talk switch

FIG. 14



Single stage MZI with asymmetrical directional couplers with input/output bends

FIG. 13

INTERNATIONAL SEARCH REPORT

ational Application No
PCT/GB 02/00494

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02F1/313

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

PAJ, EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PATENT ABSTRACTS OF JAPAN vol. 018, no. 387 (P-1773), 20 July 1994 (1994-07-20) & JP 06 110091 A (NIPPON TELEGR & TELEPH CORP), 22 April 1994 (1994-04-22) abstract	1,2,5,11
P,X	WO 01 88580 A (THANIYAVARN SUWAT ;EOSPACE INC (US)) 22 November 2001 (2001-11-22) figure 7A	1-3,11
A	US 5 653 008 A (SIM JAE-GI ET AL) 5 August 1997 (1997-08-05) abstract; figure 1	4

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Date of the actual completion of the international search	Date of mailing of the international search report
28 May 2002	05/06/2002

Name and mailing address of the ISA	Authorized officer
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FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box I.2

Claims Nos.: 6,7,8-11 as far as depending on claim 6 or 7, claim 12 and 13

Claim 6 and 7 are so broad that a meaningfull search is not possible and do not contain the essential feature of the invention (see page 5, line 13-23 and figure 8) that the optical device comprises two assymmetric couplers having waveguide portions of different width. Claims 12 and 13 refer to figures.

The applicant's attention is drawn to the fact that claims, or parts of claims, relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure.

INTERNATIONAL SEARCH REPORT

ational Application No
rC1/GB 02/00494

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